MoonLIGHT-ILN

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1 Introduction

Lunar Laser Ranging (LLR) experiment, performed since 1969 with retro-reflector arrays deployed by Apollo (Apache Point Observatory Lunar Laser-ranging Operation) 11, 14 and 15, is the only Apollo experiment, designed by a team led by C. O. Alley, D. Currie, P. Bender and Faller et al [4], still taking data today. In the past 40 years, laser ranging (LR) to these arrays has provided most of the definitive tests of the many parameters describing General Relativity (GR) [5, 7]. In addition, the analysis of the LLR data, has greatly enhanced our understanding of the interior structure of the Moon [6, 7, 8, 9]. Initially, the Apollo arrays contributed a negligible portion of the LLR error budget. Nowadays, the ranging accuracy of ground stations has improved by more than two orders of magnitude: the new APOLLO station at Apache Point, USA, is capable of mm-level range measurements [1]; MRLO (Matera Laser Ranging Observatory), at the ASI Space Geodesy Center in Matera, Italy, has re-started LR operations. Now, because of lunar librations, the Apollo arrays dominate the LLR error budget, which is a few cm. The University of Maryland, Principal Investigator for the Apollo arrays, and INFN-LNF are proposing an innovative Corner Cube Retroreflectors (CCRs) array design that will reduce the error contribution of LLR payloads by more than two orders of magnitude, down to tens of microns. This is the goal of the MoonLIGHT-ILN (Moon Laser Instrumentation for General relativity High-Accuracy Tests for the ILN) (International Lunar Network) [2], a technological experiment of INFN and of the SCF (Satellite/lunar laser ranging Characterization Facility), the CCR space test facility at LNF.

2 Science Objectives of MoonLIGHT-ILN

LLR has for decades provided the very best tests of a wide variety of gravitational phenomena, probing the validity of Einstein's theory of GR. The lunar orbit is obviously influenced by the gravity fields of the Earth and Sun, but also is sensitive to the presence of many other solar system bodies. This makes the dynamics of the lunar orbit complex, but the system is relatively pure in that non-gravitational influences (solar radiation pressure, solar wind, drag) are negligible. This makes the Earth-Moon distance an useful tool for testing the nature of gravity, constraining potential deviations from GR [3]. LLR currently provides the best constraints on fig.1.

The equivalence principle states that any mass, independent of composition, will react (accelerate) in precisely the same way when placed in a gravitational field. This is the same as saying that the inertial mass and gravitational mass of any object are precisely the same. The equivalence principle is fundamental to GR, allowing gravity to be treated as an aspect of the geometry of spacetime. In general, scalar additions to GR – motivated by string theories or quantum gravity – produce a violation of the equivalence principle and also lead to secular changes in the fundamental constants. Scalar fields are also frequently invoked to account for the apparent acceleration of the expansion of the universe. Thus tests of the equivalence principle are a vital part of understanding the interface between gravity and quantum mechanics, and in probing our cosmological fate.

The equivalence principle comes in two flavors. The WEP (Weak Equivalence Principle)

Gravity Science Measurement	Timescale	LLR Measurement Accuracy		
		Current (cm)	1 mm	0.1 mm
Weak Equivalence Principle (WEP)	Few years	$\|\Delta a/a\|<1.3\times10^{-13}$	10^{-14}	10^{-15}
Strong Equivalence Principle (SEP)	Few years	$\|\eta\|<4.4\times10^{-4}$	3×10^{-5}	3×10^{-6}
Time Variation of Gravitational Constant	~5 years	$\|\dot{G}/G\|<9\times10^{-13}\text{yr}^{-1}$	5×10^{-14}	5×10^{-15}
Inverse Square Law (ISL)	~10 years	$\|\alpha\|<3\times10^{-11}$	10^{-12}	10^{-13}
Parameterized Post-Newtonian (PPN) β	Few years	$\|\beta-1\|<1.1\times10^{-4}$	10^{-5}	10^{-6}

Figure 1: The expected improvements on the GR measurements with MoonLIGHT are shown in table, together with their measurement time scale.

relates to the composition of an object, in effect probing electromagnetic, strong nuclear and weak nuclear energy contributions. The SEP (Strong Equivalence Principle) extends to include gravity itself. The Earth-Moon system allows a test of the SEP in a way that laboratory tests cannot, in that the contribution of gravitational self-energy to the total mass-energy budget is 5×10^{-10} for the earth, but only 10×10^{-27} for typical laboratory masses. LLR allows us to ask the questions: "Do the Earth and Moon fall at the same rate toward the sun? Does the gravitational self-energy of the Earth fall toward the Sun at the same rate as the less gravity-burdened Moon? Does gravity pull on gravity in the same way it pulls on ordinary matter?". The Earth-Moon system is currently the best laboratory for answering these questions. If the SEP were to utterly fail – that is, gravitational self-energy failed to gravitate – the Moon's orbit would be shifted by 13 meters. Current LLR constrains this shift to be less than 5 mm, constituting a 4×10^{-4} constraint on violation of the SEP.

LLR can also constrain new theoretical paradigms. An example is an idea to account for the apparent acceleration of the universe by allowing gravitons to leak off of our 4-dimensional spacetime "brane" into another bulk dimension, thus weakening gravity over cosmological scales. Though small, such a process would have an impact on the lunar orbit, causing it to precess by effectively invalidating the $1/r^2$ force law of gravity. LLR needs to see a factor of 15 improvement to reach this level of sensitivity to new physics.

Furthermore much of our knowledge of the interior of the Moon is the product of LLR [8, 9, 10, 11], often in collaboration with other modalities of observation. These physical attributes of the lunar interior include Love number of the crust, the existence of a liquid core, the Q of the Moon, the physical and free librations of the Moon and other aspects of lunar science.

3 2nd Generation of Lunar Laser Ranging

The general concept of the second generation of LLR is to consider a number (notionally eight) large single CCRs. Each of these will have a return that, with a single photoelectron detection system such as current APOLLO system located at the Apache Point Observatory, can be used to determine the range to the limit determined by the librational effects of the current arrays and the laser pulse length. By using single CCRs, the return is unaffected by the libration. That is, there is no increased spread of the FWHM (Full Width at Half Maximum) due to the CCR and the librational effects. We plan to use eight such single reflectors spread over tens of meters. The return from each of the CCRs will be registered separately and can be identified by comparison with the nominal lunar orbit and earth rotational parameters. This is shown schematically in Fig.2.

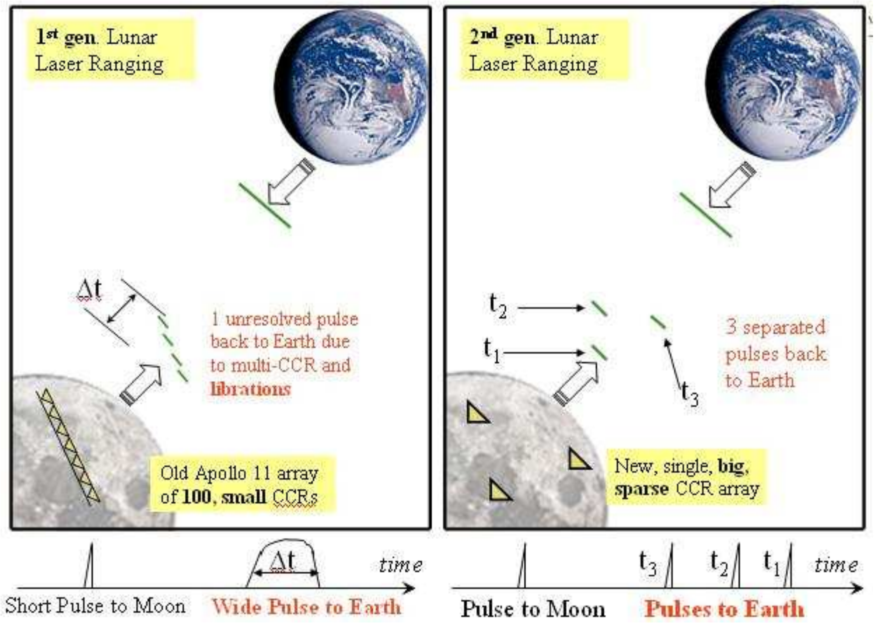

Figure 2: *Concept of the 2nd generation of Lunar Laser Ranging*

4 The New Maryland/Frascati Payload

We currently envision the use of 100 mm CCRs composed of T19 SupraSil I. This is the same material used in LLRA (Lunar Laser Ranging Array) 20^{th} and both LAGEOS satellites. This will be mounted in an aluminum holder that is thermally shielded from the Moon surface, in order to maintain a relatively constant temperature through the lunar day and night. It is also isolated from the CCR, by two co-axial "gold cans", so the CCR receives relatively little thermal input due to the high temperature of the lunar day and the low temperature of the lunar night. The mounting of the CCR inside the housing is shown in Fig.3. KEL-F could be used for this mounting (its used in LAGEOS) due to its good insulating, low out-gassing and non-hygroscopic properties.

5 Technical challenges of the MoonLIGHT CCR

The primary technical objectives of the LLRRA-21 (Lunar Laser Retro Reflector Array) are to provide adequate laser return to Earth ground stations and to be stable over long term, decades, with respect to the center of mass of the Moon. The major technical/engineering challenges that follow from the technical objective are then:

- Fabricate a large CCR with adequate homogeneity and that meet the required tolerances, mentioned in the previous section.
- Thermal control to reduce thermal gradients inside the CCR to acceptable levels. Thermal gradients produce index of refraction gradients, which cause beam spread and low return.

Figure 3: Views of current design of the MoonLIGHT/LLRRA21 CCR: (a) fully assembled; (b) exploded view with its internal mounting elements and outer aluminum housing.

- Emplacement goal of long-term stability of $10\mu m$ with respect to the Center of Mass of the Moon.

The large diameter of the CCR introduces a great challenge in its fabrication, the availability of such material of the required homogeneity, the fabrication and polishing procedures and the measurement methods. The angle between the three back reflecting faces, which govern the shape of the pattern, have a more challenging tolerance of ± 0.2 arcsec; this is more restrictive by a factor of 2.5 than the current state of the art for SLR (Satellite Laser Ranging) CCR fabrication. The material choice is primarily driven by three requirements:

- extremely uniform index of refraction (very good homogeneity)
- resistance to darkening by cosmic radiation
- low solar radiation absorption

To satisfy these requirements, this CCR has been fabricated with SupraSil 1. For the next generation of CCRs, LLRRA-21, we plan to use SupraSil 311 which has even better homogeneity.

The optical performance of the CCR is determined by its Far Field Diffraction Pattern (FFDP), which represents the intensity of the laser beam reflected back to the ground by the CCR. Figure 4 is a simulation of the FFDP of the LLRRA-21 (performed with the software CodeV) according to its dimensions and angle specifications; at the correct velocity aberration the intensity (calculated in optical cross section) should have a value which guarantees that enough photons come back to the ground station. Optical cross section is an intrinsic characteristic of CCRs or LRAs, and it is defined as follows:

$$\sigma_{CCR} = I_{CCR/MIRR} \left(\theta_x, \theta y\right) 4\pi \left(\frac{A_{CCR}}{\lambda}\right)^2 \tag{1}$$

Where $I_{CCR/MIRR}$ is the intensity of the FFDP of the CCR, at a certain point of the (θx, θy) plane, referred to a perfect mirror of the same aperture as the CCR, λ is the laser wavelength and A_{CCR} is the area of the aperture of the CCR. One of the most critical challenges of this new

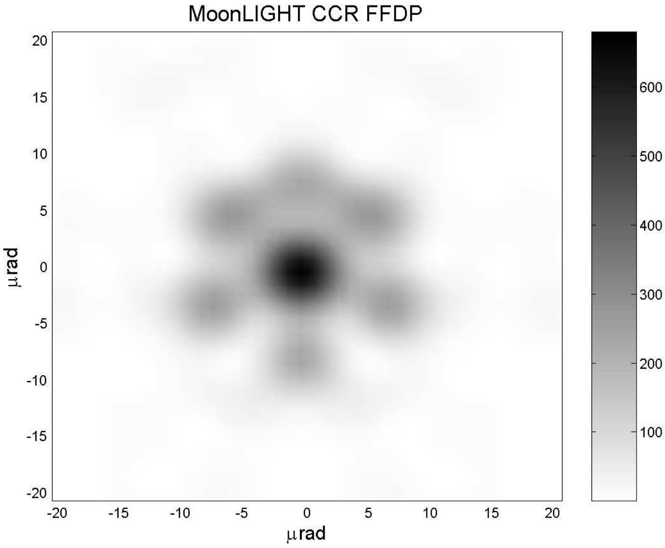

Figure 4: *FFDP of LLRRA-21 under its design specification of offset angles (0.0" 0.0" 0.0"). Grid is in angular dimensions (μrad)*

model is the issue of the thermal gradient. Since the index of refraction of the fused silica depends upon temperature, a thermal gradient inside the CCR will cause the index of refraction to vary within the CCR and thus modifying the FFDP. In Figure 6, is represented the average intensity over the velocity aberration for the LLRRA-21 at Standard Temperature and Pressure (STP). At the velocity aberration for the Moon, $\sim 4\mu rad$, we will test thermal perturbations and, if needed, developed an optimized design to control the drop of FFDP intensity to an acceptable level. For this reason we need to understand in detail how the external factors heat the CCR and in what magnitude, either on the Moon or on a satellite. This is accomplished using dedicated programs developed in parallel at LNF and UMD (University of Maryland). To perform these simulations we use Thermal Desktop, a software package of C&R Technologies of Boulder CO. Then using softwares IDL and CodeV we translate these thermal gradients into the effects on the FFDP of the CCR. There are three primary sources of heat that cause thermal gradients; here we briefly describe their effect:

- *Absorption of solar radiation within the CCR*: during a lunar day, the solar radiation enters the CCR and portions of this energy are absorbed by the fused silica. Since the different wavelengths in the solar radiation are absorbed with different intensity, according to fused silica absorptivity characteristic, the heat is deposited in different parts of the CCR.

- *Heat flux flowing through the mechanical mounting tabs*: if the CCR is at a temperature that is different than the housing temperature there will be a flux of heat passing into (or out of) the CCR through the holding tabs. Conductivity of the mounting rings should be reduced.

- *Radiation exchange between the CCR and the surrounding pocket*: in the case of the Apollo LRAs, the back surfaces of the CCRs view the aluminum that makes up the housing, machined with a relative high emissivity/absorptivity. If the temperatures of the CCR and the aluminum are different there is a radiation exchange of thermal energy, which in turn causes a flux in the CCR as the heat exits out of the front face to cold space. In the Apollo array this

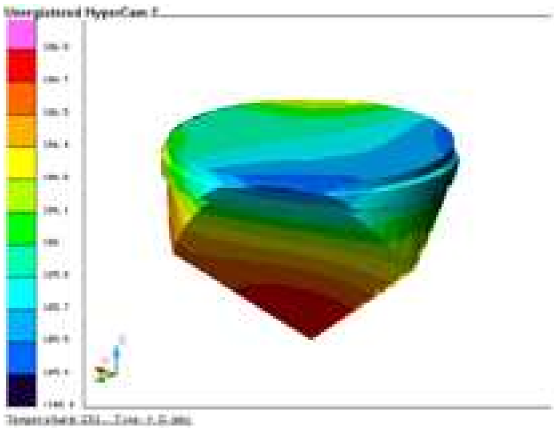

Figure 5: *Typical distribution of temperature inside the CCR for a given set of conditions.*

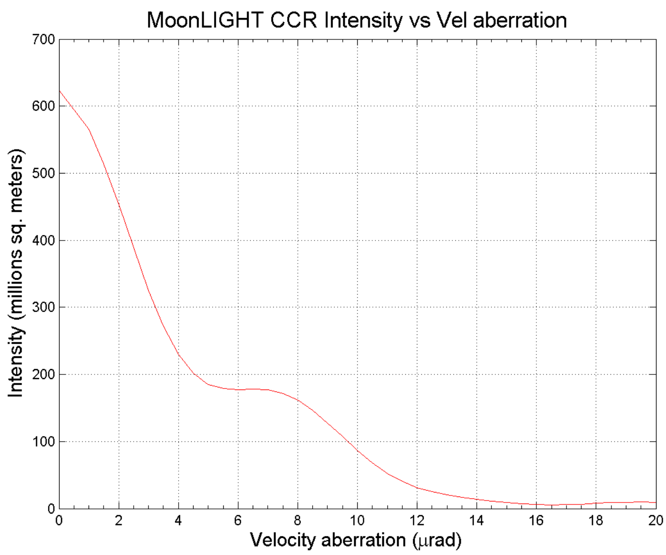

Figure 6: *Average intensity over velocity aberration of an unperturbed MoonLIGHT CCR*

is not been a serious issue, but the bigger dimensions of the LLRRA-21 complicate things, and we need to reduce this effect. Thus we enclose the CCR into two thermal shields, with a very low emissivity (2%), that should prevent this radiative heat flow.

Thermal simulations performed on the current configuration show that currently the variation of the ΔT between the front face and the tip of the CCR is within 1K. We are still proceeding to optimize this further, both with optical design procedures and with thermal stabilization of the overall housing.

As mentioned earlier, to achieve the desired accuracy in the LLR, a long term stability is needed with respect the center of mass of the Moon; to attain this we must understand and simulate the temperature distribution in the regolith (and its motion), the effects of a thermal blanket that will be spread about the CCR and the effects of heat conduction in the INVAR supporting rod. A locking depth is chosen such that the thermal motion effects are small ($\sim 1m$). The placement of the thermal blanket further reduces thermal effects and also reduces the effects of conduction in the supporting rod.

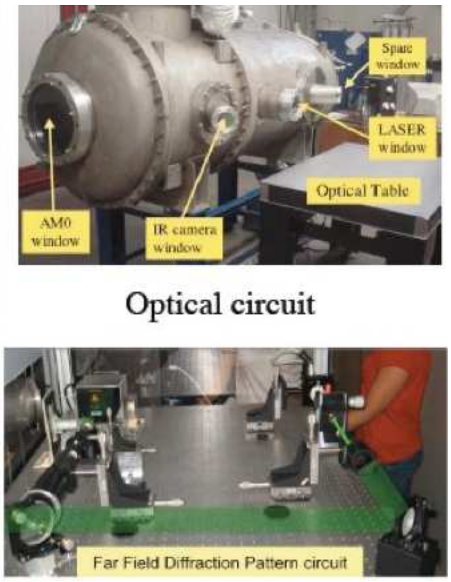

Figure 7: *SCF cryostat and optical table.*

6 Thermal-optical-vacuum SCF-Tests in Frascati

SCF, fig.: 7, at LNF/INFN in Frascati, Italy, is a cryostat where we are able to reproduce the space environment: cold (77 K with Liquid Nitrogen), vacuum, and the Sun spectra. The SCF includes a Sun simulator (www.ts-space.co.uk), that provides a 40 cm diameter beam with close spectral match to the AM0 standard of 1 Sun in space ($1366.1 W/m^2$), with an uniformity better than $\pm 5 W/m^2$ over an area of 35 cm diameter. Next to the cryostat we have an optical table, where we can reproduce the laser path from Earth to the Moon, and back, studying the FFDP coming back from the CCR to the laser station, useful to understand how good is the optical behavior of the CCR. The SCF-Test (Dell'Agnello et al. 2011) is a new test procedure to characterize and model the detailed thermal behavior (fig.: 8 and 9) and the optical performance of laser retroreflectors in space for industrial and scientific application, never before been performed. We perform a SCF-

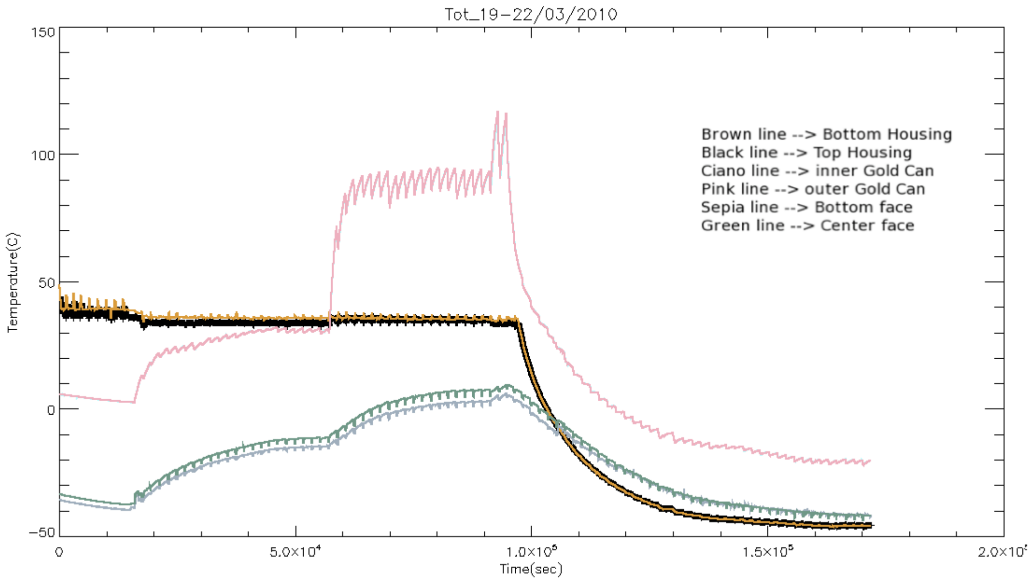

Figure 8: MoonLIGHT/LLRRA-21 flight CCR temperature variations of various housing parts and of CCR (19-22/March/2010).

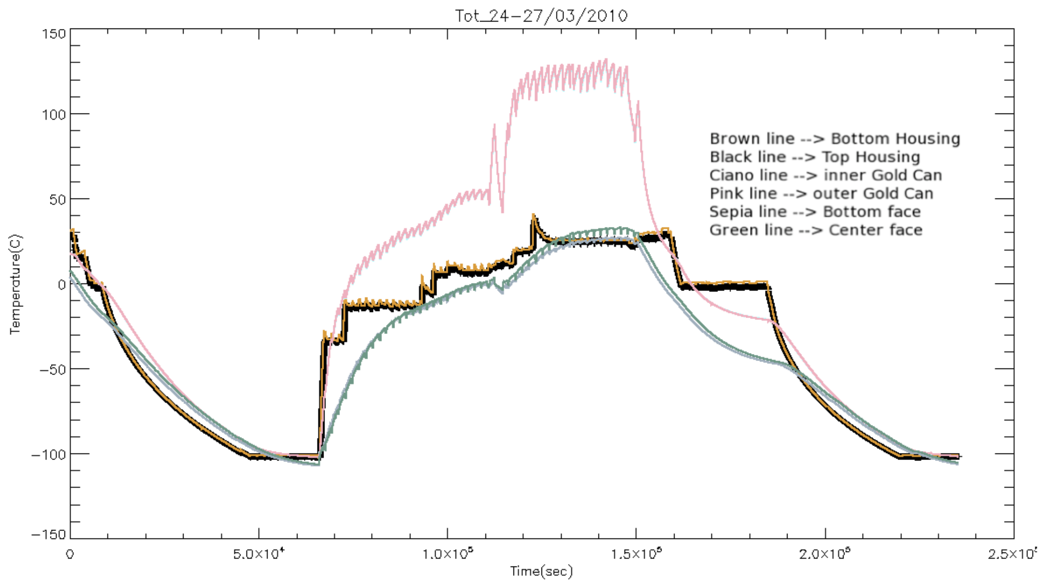

Figure 9: MoonLIGHT/LLRRA-21 flight CCR temperature variations of various housing parts and of CCR (24-27/March/2010).

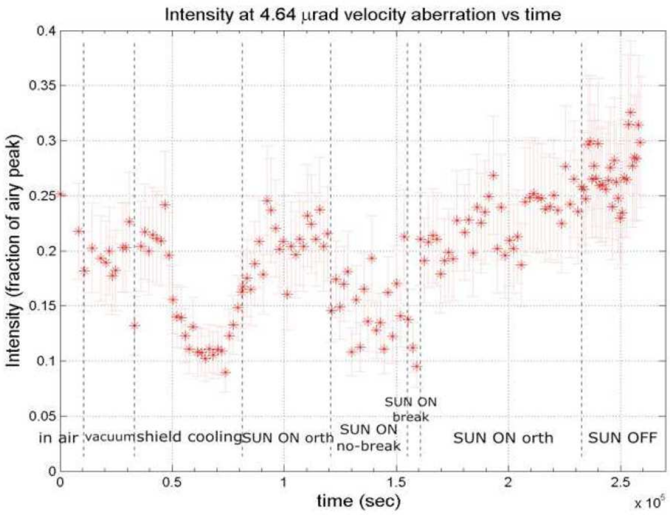

Figure 10: MoonLIGHT/LLRRA-21 flight CCR FFDP intensity variation at Moon velocity aberrations (2V/c) during tests (time subdivision refers to the fig.: 8).

Test on the MoonLIGHT CCR to evaluate thermal and optical performances in space environment. About thermal measurements we use both an infrared (IR) camera and temperature probes, which give a real time measurements of all components of the CCR and its housing. In particular we look at the temperature difference from the front face to the tip, studying how the FFDP changes during the different thermal phases. This is the best representative of the thermal distortion of the return beam to the Earth. Various configurations and designs of the CCR and the housing have been and are being tested in the SCF Facility. In fig.: 10 and 11 is shown the MoonLIGHT/LLRRA-21 flight CCR FFDP intensity variation at Moon velocity aberrations (2V/c) during key points of the SCF-Test: (1) in air, (2) in vacuum, (3) during chambers shields cooling, (4) Sun on orthogonal to the CCRs face with the housing temperature controlled at $T = 310K$, (5) Sun on at 30° of inclination (no break-through), (6) Sun on at −30° of inclination (break-through), (7) Sun on orthogonal with the housing temperature left floating. From this graph we can deduce that the intensity decreases during no orthogonal lighting of the CCR, in particular when the Sun enters in the housing cavity during the break-through phase. This effect is due to a strong increase of the "Tip-Face thermal gradient during these two phases of the test. When the housing temperature is left floating, the intensity slightly increases because the "Tip-Face" gradient is reducing.

7 Analysis of lunar laser ranging data

In order to analyze LLR data we used the PEP (Planetary Ephemeris Program) software, developed by the CfA, by I. Shapiro et al. starting from 1970s. PEP was designed not only to generate ephemerides of the planets and Moon, but also to compare model with observations (Reasenberg et al., 1979; Chandler et al., 1996; Battat et al., 2007). One of the early uses of this software was the first measurement of the geodetic precession of the Moon (Shapiro et al., 1988). PEP asserts that the solar system barycenter frame is an inertial frame. Thus far, there is no evidence to suggest otherwise. Where the solar system barycenter frame non-inertial, then one would expect to see residuals between observations and calculations (the OC residuals) due to unmodeled coriolis-type

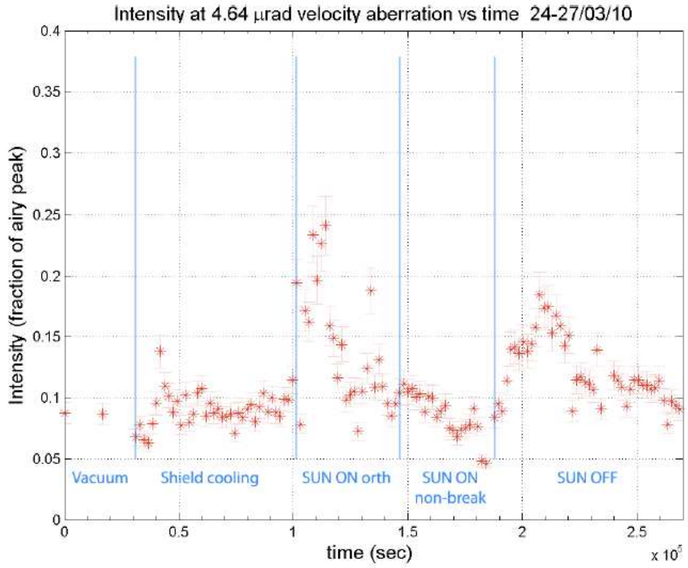

Figure 11: MoonLIGHT/LLRRA-21 flight CCR FFDP intensity variation at Moon velocity aberrations (2V/c) during tests (time subdivision refers to the fig.: 9).

forces. Although the forces are calculated in the solar system barycenter frame, PEP reports the positions and velocities of the solar system bodies with respect to the Sun center of mass (Solar System Barycenter, SSB). The heliocentric coordinates of the solar system barycenter are also computed. Nevertheless, the physics is performed in the (inertial) SSB frame; the heliocentric coordinates are derived quantities. The PEP software has enabled constraints on deviations from standard GR physics. For example, it can be used to estimate PPN (Parametrized Post Newtonian) parameters β and γ; relative deviation from the geodetic precession, K_{GP} and the time variation of the gravitational constant, $\frac{\dot{G}}{G}$. The spacetime torsion equations of motion March et al. (2011a,b) can be included in PEP and constrained with all LLR data, including the newest APOLLO data (at the present the published constraints on spacetime torsion are calculated using LLR data from other stations). The APOLLO station (Battat et al., 2009; Murphy et al., 2000, 2002) is located at the Apache Point Observatory in southern New Mexico and utilizes a 3.5 m telescope. Compared to MLRS, the 3.5 m telescope of APOLLO has a factor of 20 greater light-collecting area. The greater return rate of APOLLO allows us to study systematic effects improving statistical error. The main goal of APOLLO is to push LLR into the millimeter range precision, this will improve the determination of fundamental physics parameters of about few order of magnitude (see Table 1). We have performed a preliminary analysis of LLR data from three different stations: McDonald Observatory in Texas, Grasse in France and APOLLO in New Mexico. The latter station provides the best quality data since 2006. On March 25, 2010, the Matera Laser Ranging Observatory in Italy (MLRO, led by G. Bianco) recorded LLR echos from the array of Apollo 15.
The histograms in Fig.11 show photon-by-photon data and are used to form a single LLR normal point of the Apollo 15 array taken by the APOLLO station (led by T.W. Murphy) on November 19, 2007. A normal point contains several information e.g. date of observation, atmospheric conditions, as well as time of flight, data quality and CCR arrays.
The APOLLO instrumental accuracy (in terms of laser, detector, timing electronics, etc) shown by the fiducial returns in Fig. 11 is a root mean square contribution of 120 ps (18 mm). From a

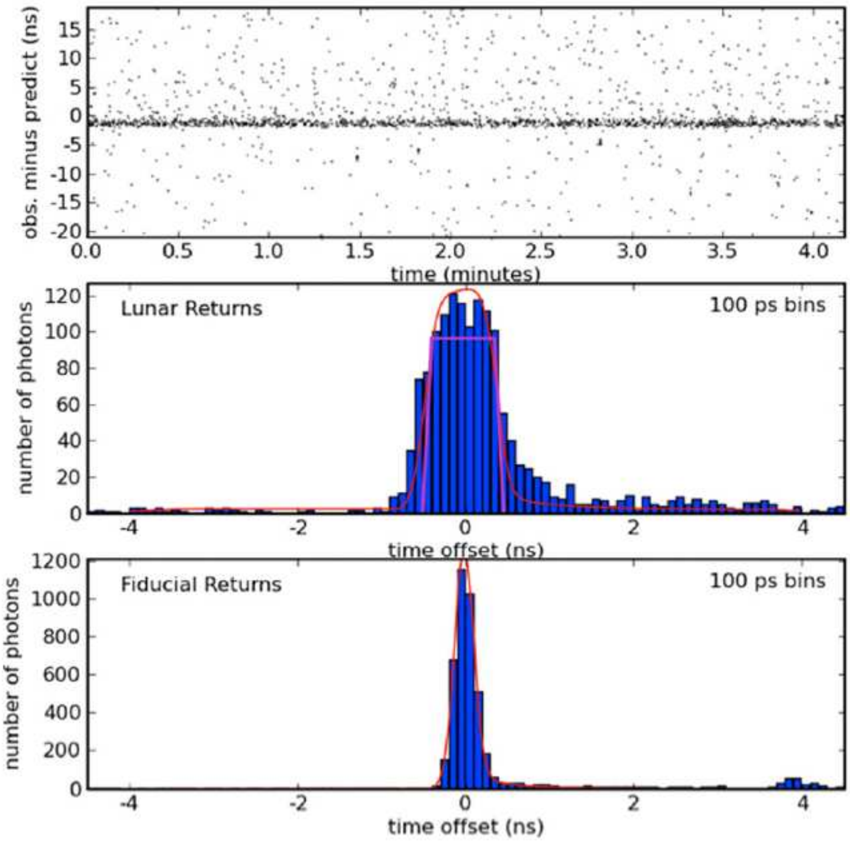

Figure 12: Example run of Apollo 15. In the plot, the top panel shows a 40 ns window of observed round trip time minus the predicted range. Background noise and detector dark current appear as scattered dots, while the lunar return is in the middle. The middle panel shows a histogram of the lunar returns, while the bottom panel shows the local fiducial CCR return, fitted by the red Gaussian. The Lunar return is additionally spread by the tilted reflector array modeled by the superimposed magenta trapezoidal shape

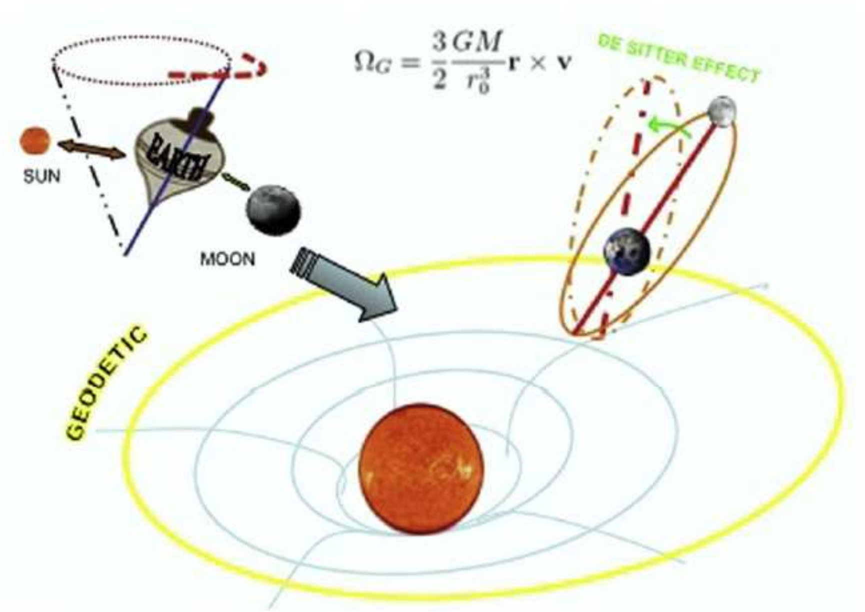

Figure 13: KGP is the relative deviation of geodetic precession from the GR value.

comparison between the middle and the last plot we can see how the tilt in the arrays affects the accuracy of the ranging measurements. The model parameter estimates are refined by minimizing the residual differences, in a weighted least-squares sense, between observations (O) and model predictions (C, stands for Computation), OC. Observed is round-trip time of flight. Computed is modeled by the PEP software.

8 Determination of the geodetic precession

With PEP software we have measured relative deviation from the GR value (deviation from zero) of the geodetic precession (the Sitter effect in Fig. 12), expressed by the K_{GP} parameter. We have used all the data available to us from Apollo CCR arrays: Apollo 11, Apollo 14 and Apollo 15. Results are reported in two tables, one until 2003, acquired with data by the old ILRS (International Laser Ranging Service) stations (Table 2) and one with data from 2007 to 2009 acquired by the new APOLLO station (Table 3). Results described in the tables are obtained fixing the parameters to their GR values:

$$\beta = \gamma = 1, \frac{\dot{G}}{G} = 0 \tag{2}$$

Using APOLLO LLR data, the estimated value is slightly larger than for the old stations (see Table 3). Nominal errors returned by the fit are significantly smaller than the value of K_{GP}, and smaller than the best published values. Therefore, we want to use the data to understand and estimate independently the size of the error budget. As a systematic check of the stability of the K_{GP} estimate, we have also performed a fit using every single old station. The results are shown in Table 4. These preliminary measurements are to be compared with the best result published by JPL (Jet Propulsion Laboratory) (Williams et al., 2004) ($K_{GP} = (-1.9 \pm 6.4)10^{-3}$), obtained using a completely different software package, developed over the last 40 years. On the contrary,

Table 2
Estimates of geodetic precession, K_{GP}, with the dataset from MLRS, MLR2 and CERGA stations.

Parameter	GR initial value	Final value
K_{GP}	0	0.009

Table 3
Estimates of geodetic precession, K_{GP}, with the new dataset from APOLLO station.

Parameter	GR initial value	Final value
K_{GP}	0	−0.0096

Table 4
Estimates of geodetic precession, K_{GP} using every single old station.

Station	K_{GP}
CERGA	−0.016
MAUI	0.0060
MLR2	0.0095
TEXL	−0.044

after the original 2% K_{GP} measurement by CfA (Center for Astrophysics) in 1988, the use of PEP for LLR has been resumed only since a few years, and it is still undergoing the necessary modernization and optimization.

9 Conclusions

We have created a unique facility and a new industry-standard laboratory test to validate the thermal and optical behavior of CCR in space. The experimental apparatus and the test procedures are described in great detail in Dell'Agnello et al. (2011) and ETRUSCO (2011). The MoonLIGHT experiment is the result of a collaboration between two teams: LLRRA21 and the INFN-LNF. With Moon- LIGHT we are exploring improvements in both instrumentation and the modeling of CCR. For the SCF-Test, we can conclude that the intensity of the FFDP decreases during no orthogonal lighting of the CCR, in particular when the Sun enters in the housing cavity during the test. We have obtained a measurement of geodetic precession that is consistent with the prediction of GR with a competitive uncertainty. This is an interesting and promising preliminary study.

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